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Unexpected C═C Bond Formation via Doubly Dehydrogenative Coupling of Two Saturated sp^3 C−H Bonds Activated with a Polymolybdate

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The C−H bond activation and functionalization have been the focus of intense research effort in the scientific and industrial community in recent years.[1] While a lot of excellent results have been achieved, the direct coupling reactions between two sp^3 C−H bonds are still a challenge.[2] Recently, the catalytic activation of sp^3 C−H bonds adjacent to a nitrogen atom has become a promising transformation to the buildup of a C−C single bond.[3] In this communication, we wish to report that two α C−H bonds in aliphatic primary amines can be activated by a polymolybdate, and a C═C double bond forms unexpectedly via the doubly dehydrogenative coupling (DDHC) reaction. These findings maybe open a new road to activate and functionalize the C−H bonds.

The formation of carbon−carbon double bonds is one of the most useful and fundamental reactions in chemistry.[4] Among a number of useful transformations to make C═C double bonds,[4] the dehydrogenation reactions of C−H groups, including intramolecular dehydrogenative olefination (IDO) and intermolecular doubly dehydrogenative coupling (IDDC) (Figure 1), are the most exciting and attractive strategies, due to its simplicity, atomic economy, and high efficiency. Nowadays, considerable progress has been made in the construction of C═C double bonds via IDO reaction of two neighboring sp^3 C−H groups.[5,6] However, the IDDC protocol has never been developed, inasmuch as the simultaneous activation of two sp^3 C−H groups on one carbon center is rather difficult. The direct formation of C═C double bonds according to such a strategy is still a formidable challenge.

In light of Lunsford's work, who reported that MoO_3 can effectively activate the sp^3 C−H bond,[7] we felt that polymolybdates might have the same role on the C−H bond activation as that of MoO_3 since polyoxometalates, as a unique class of "molecular state" metal oxides,[8] can be used as the substitutes or models of metal oxides in the catalytic transformation of organic chemicals.[9−11] In an attempt to activate the saturated C−H bond of *n*-propylamine with polymolybdates, we discovered, unexpectedly, that two C−H groups adjacent to the N atom had been activated and subsequently coupled dehydrogenatively to form a dimeric, organoimido-substituted hexamolybdate containing a C═C double bond, $[Bu_4N]_4[Mo_6O_{18}NC(C_2H_5){=}C(C_2H_5)NMo_6O_{18}]$, **1**.

Compound **1** was yielded by a reflux reaction of *n*-propylamine hydrochloride, tetrabutylammonium α-octamolybdate, and *N*,*N′*-dicyclohexylcarbodiimide (DCC) in dry acetonitrile.[12] It was first detected to be a novel product by ^{1}H NMR and ^{13}C NMR studies (Figure 1S and 2S). Compared to the free *n*-propylamine ligand and the corresponding uncoupled monosubstituted imidohexamolybdate, $[Bu_4N]_2[Mo_6O_{18}NCH_2CH_2CH_3]$, **2**, it was surprising that the signal (a triplet peak at 2.53 and 4.42 ppm in *n*-propylamine and **2**, respectively) from two H atoms near to the N atom disappeared in the ^{1}H NMR spectroscopy of **1**, suggesting that such two H atoms had dehydrogenated via the activation of C−H bonds and had been replaced by a non-hydrogen functional group. Further investigation on its ^{13}C NMR spectroscopy implied that such a new functional group is the C═C double bond with a characteristic chemical shift at 161.2 ppm, which is silent in the DEPT mode!

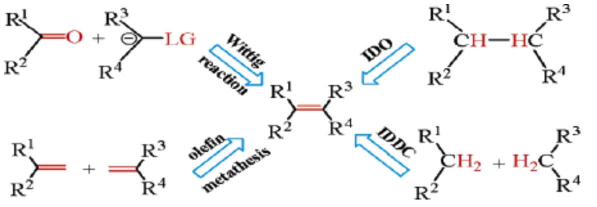

Figure 1. Four important strategies for the synthesis of alkenes (LG = leaving group).

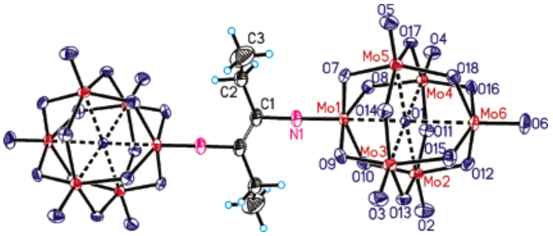

Figure 2. ORTEP drawings of the cluster anion of **1**.

The molecular structure of compound **1** was definitely confirmed by its X-ray single-crystal diffraction investigation. The structure of the cluster anion of **1** is shown in Figure 2. As expected, the carbon atom (C1) near the nitrogen atom (N1) has doubly dehydrogenated indeed and dimerized via the formation of a C═C double bond: The short C1−C1#1 (symmetry code #1: $-x$, $-y$, $-z+1$) distance of 1.250(11) Å is typical of carbon−carbon double bond; also, the sum of three bond angles (C1#1−C1−N1 119.0(7)°, C1#1−C1−C2 127.7(7)°, N1−C1−C2 113.2(4)°) around the C1 atom is exactly the 360° of that of a sp^2 carbon atom. The so-resulted cluster anion is composed of two terminally substituted imidohexamolybdate cages[13] bridged by a tetrasubstituted, conjugated, rigid ethylene system. Presumedly due to large bulk, the two hexamolybdate cages in the cluster anion of **1** are connected, in a trans manner, to the ethylene unit via a Mo≡N triple bond[14] with the Mo1−N1 bond length of 1.724 (3) Å and the C1−N1−Mo1 bond angle of 171.9 (5)°. The whole cluster anion has crystallographically imposed ideal C_i symmetry with the inversion center located at the middle of the C═C bond.

While the structure of **1** was validated, we then investigated the optimum reaction conditions, including the amount of each raw material, temperature, and the reaction time, which can be obtained by monitoring the reaction system with UV−vis by determining its characteristic maximum absorption at 470 nm, and a preferred protocol is given in Supporting Information. Compared to the previous methods to activate the sp^3 C−H bond, this novel reaction routine has a lot of advantages: no noble metals are used; its reaction conditions are much milder with easy bench operation;

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Scheme 1. The Synthesis of Compound **1** and Analogues

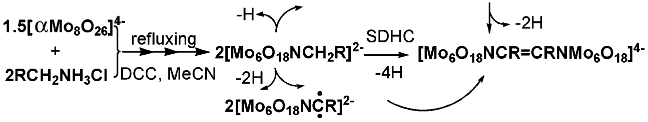
$$3(Bu_4N)_4[\alpha Mo_8O_{26}] + 4RCH_2NH_3Cl + 6DCC \xrightarrow[\text{refluxing}]{\text{MeCN}} 2(Bu_4N)_4[Mo_6O_{18}NCR{=}CRNMo_6O_{18}] + 6DCU + 4H_2 + 4Bu_4NCl$$

Table 1. Comparative List of the Products and Yields with Different Amines

entry	primary amines	product	yield (%)
1	*n*-propyl	$[Mo_6O_{18}NC(C_2H_5){=}C(C_2H_5)NMo_6O_{18}]^{4-}$, **1**	62
2	ethyl	$[Mo_6O_{18}NC(CH_3){=}C(CH_3)NMo_6O_{18}]^{4-}$, **3**	50
3	*n*-butyl	$[Mo_6O_{18}NC(C_3H_7){=}C(C_3H_7)NMo_6O_{18}]^{4-}$, **4**	56
4	*n*-hexyl	$[Mo_6O_{18}NC(C_5H_{11}){=}C(C_5H_{11})NMo_6O_{18}]^{4-}$, **5**	57
5	*n*-dodecyl	$[Mo_6O_{18}NC(C_{11}H_{23}){=}C(C_{11}H_{23})NMo_6O_{18}]^{4-}$, **6**	52
6	*n*-octadecyl	$[Mo_6O_{18}NC(C_{17}H_{35}){=}C(C_{17}H_{35})NMo_6O_{18}]^{4-}$, **7**	53
7	*n*-propyl + *n*-butyl	$[Mo_6O_{18}NC(C_2H_5){=}C(C_3H_7)NMo_6O_{18}]^{4-}$, **8**	36[a]
8	*n*-propyl + *n*-hexyl	$[Mo_6O_{18}NC(C_2H_5){=}C(C_5H_{11})NMo_6O_{18}]^{4-}$, **9**	34[a]

[a] Two homocoupling products have also been confirmed by ESI at ca. 10% yields.

Scheme 2. Plausible Mechanisms for the Formation of **1** and Analogues (SDHC = Synergetic Dehydrogenative Coupling)



and particularly, two sp^3 C−H bonds at one carbon atom are both activated, resulting in the formation of the C═C double bond.

With the optimized reaction conditions established, various substrates were subjected to this doubly dehydrogenative coupling reaction. To our delight, this reaction indeed takes place for a number of aliphatic primary amines; the general reaction routine is shown in Scheme 1, and representative results are listed in Table 1. While there were no coupling products detected by ESI mass spectroscopy in the case of methylamine and benzylamine, various primary alkylamines, including the long-chain *n*-dodecylamine and *n*-octadecylamine (Table 1, entries 5 and 6), reacted smoothly with α-octamolybdate under the standard reaction conditions, and the desired products were obtained in good yields. In addition, when two different aliphatic amines (Table 1, entries 7 and 8) were used, the desired cross-coupling products were also formed in moderate yields. Such a result provides us a chance to conveniently arrange the C═C double bond into different positions of the alkyl chain of the coupling products. All the products in Table 1 have been characterized with ^{1}H NMR, IR, UV−vis, and ESI-MS. In addition, the cross-coupling product **9** was further substantiated by X-ray single-crystal diffraction investigation (Figure 3S).

While the precise mechanism of the IDDC reaction will have to await detailed experiments in progress probing the mechanism, one's first thoughts turn to something like a radical coupling, or possibly a biradical/carbene intermediate, as shown in Scheme 2. Consistent with Scheme 2, heating a dry acetonitrile solution of $[Bu_4N]_2[Mo_6O_{18}NCH_2CH_2CH_3]$, **2**, at refluxing temperature for 12 h did give the coupling product **1** in ca. 10% yield and at a rate that is kinetically competent to account for the observed reaction from the octamolybdate starting material. Interestingly, use of $[Mo_6O_{19}]^{2-}$ did not yield the coupling product, **1**, but instead yielded the reduced $[Mo_6O_{19}]^{3-}$ and oxidized amines. This means that the octamolybdate is a key to allowing the imidohexamolybdate intermediate in Scheme 2 to form.

In conclusion, a novel protocol to produce the C═C double bonds was developed via the dehydrogenative coupling of two sp^3 C−H bonds from aliphatic primary amines. The present work implies that the C═C double bonds can be elaborated directly from the functionalization of two saturated C−H bonds, and polymolybdates are promising reagents in the activation of C−H bonds. The scope, mechanism, and potential applications of this method in organic transformation are under study in our laboratory.

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Supporting Information Available: Synthetic details and characterization data for compounds **1**−**9**, X-ray crystallographic data for **1** and **9**. This material is available free of charge via the Internet at http://pubs.acs.org.

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